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(54) SYSTEM AND METHOD FOR RECEIVING HIGH SPECTRAL EFFICIENCY OPTICAL DPSK SIGNALS

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H04B 10/06 (2006.01)

(52) **U.S. Cl.** **398/202**; 398/212; 398/213; 398/208; 398/209; 398/183; 398/188

(58) **Field of Classification Search** 398/183, 398/188, 202, 212, 208, 209, 213, 214, 158, 398/159, 25, 26, 27, 38, 79, 160
See application file for complete search history.

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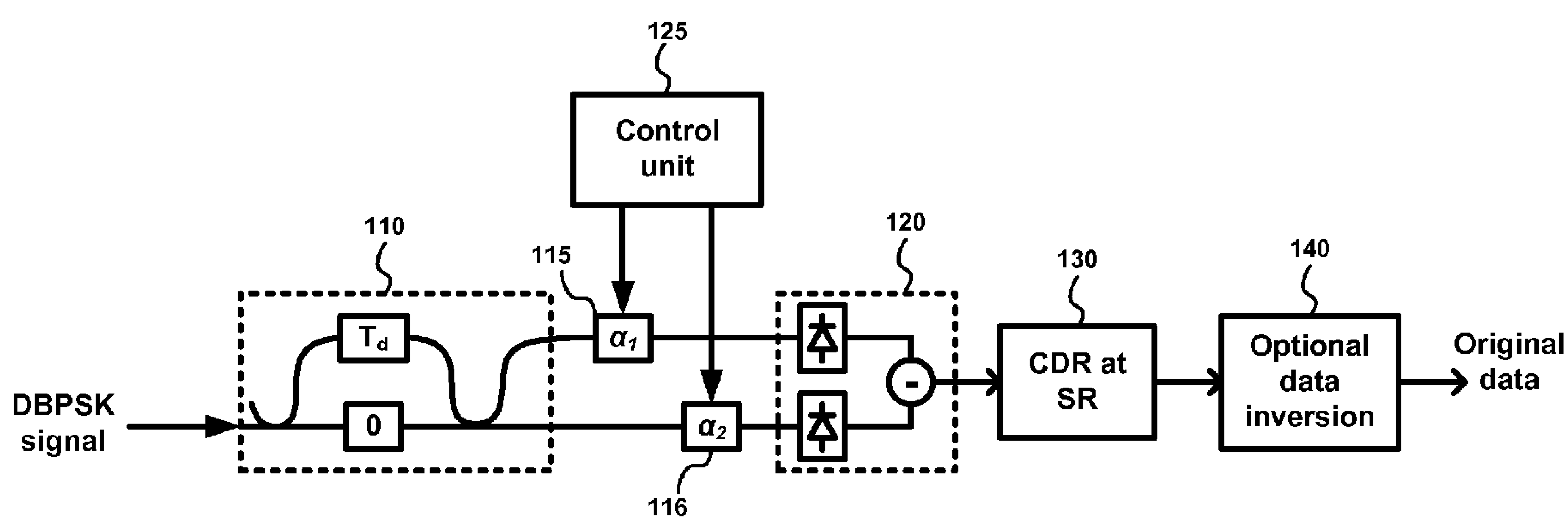
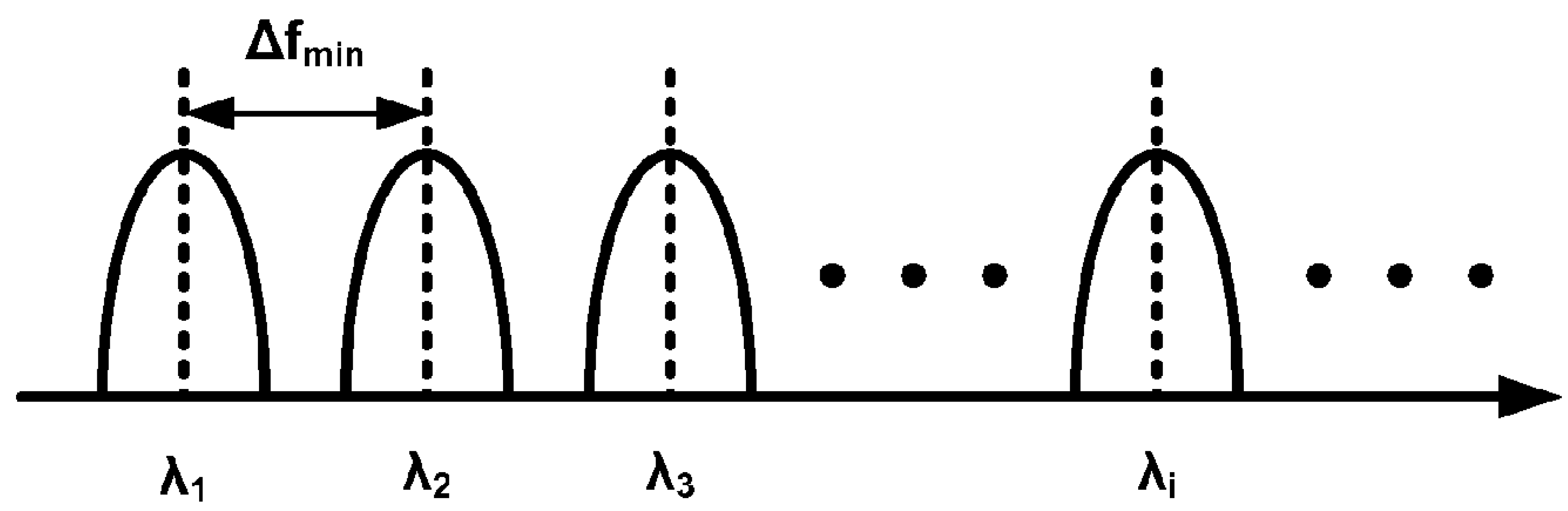
(57) **ABSTRACT**

Apparatus and methods are provided for receiving differential phase-shift keyed (DPSK) optical signals subjected to tight optical filtering, such as may be experienced by 40 Gb/s and 100 Gb/s channels in a dense wavelength division multiplexing (DWDM) communications system with 50 GHz channel spacing. An optical DPSK receiver is described which employs an optical delay interferometer (ODI) demodulator having a free spectral range (FSR) that is larger than the symbol rate (SR) of the DPSK signal to be demodulated. The receiver includes means for introducing an additional power imbalance between the outputs of the ODI demodulator, and the additional power imbalance may be related to the ratio of FSR to SR. The additional power imbalance increases the signal tolerance to tight optical filtering, thereby achieving high spectral efficiency in applications such as DWDM.

16 Claims, 5 Drawing Sheets

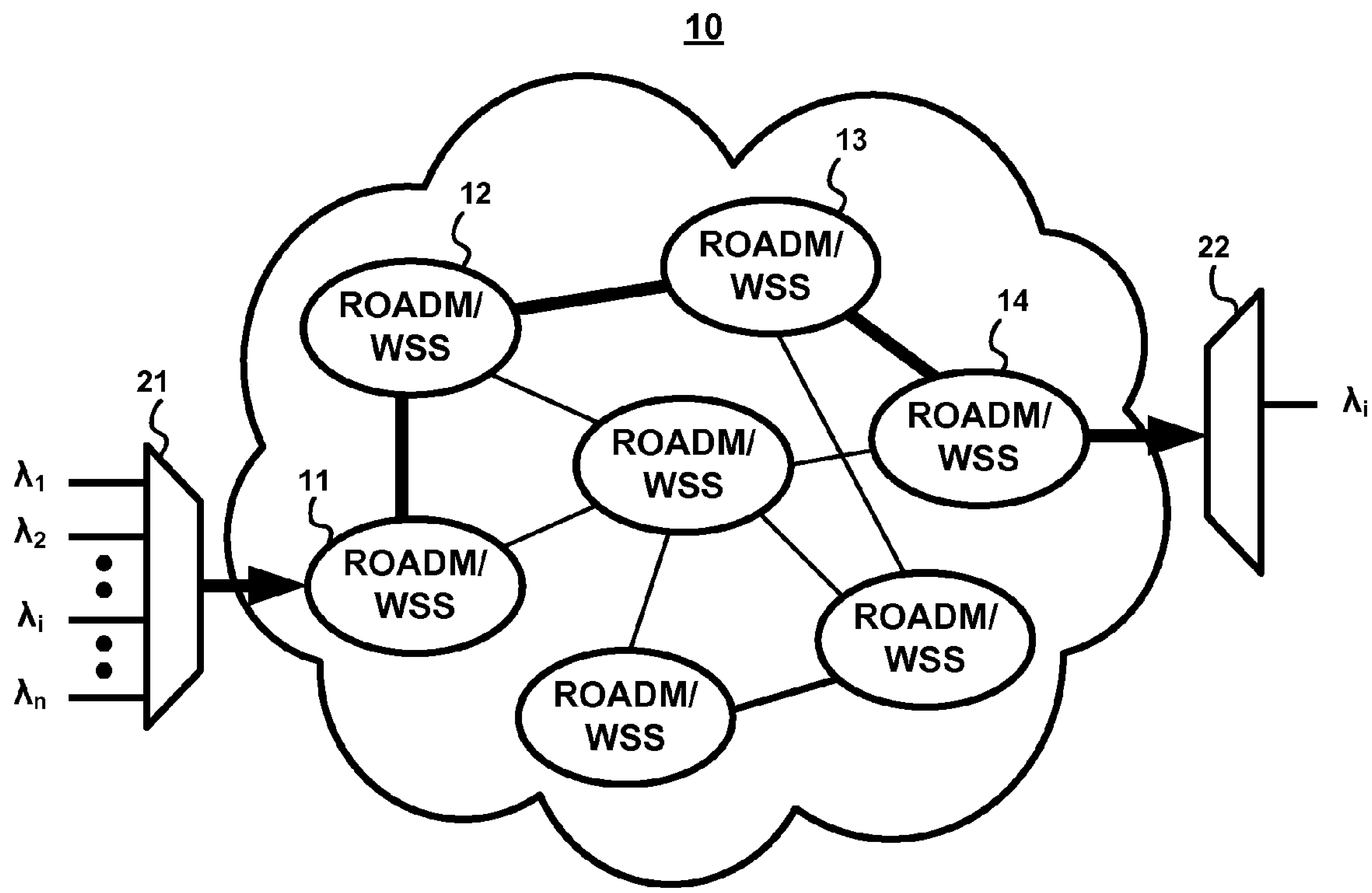
100





Δf_{min}
λ_1
λ_2
λ_3
λ_i

FIG. 1A



10
12
13
14
21
22
11
ROADM/ WSS
ROADM/ WSS
ROADM/ WSS
ROADM/ WSS
ROADM/ WSS
ROADM/ WSS
ROADM/ WSS
λ_1
λ_2
λ_i
λ_n
λ_i

FIG. 1B

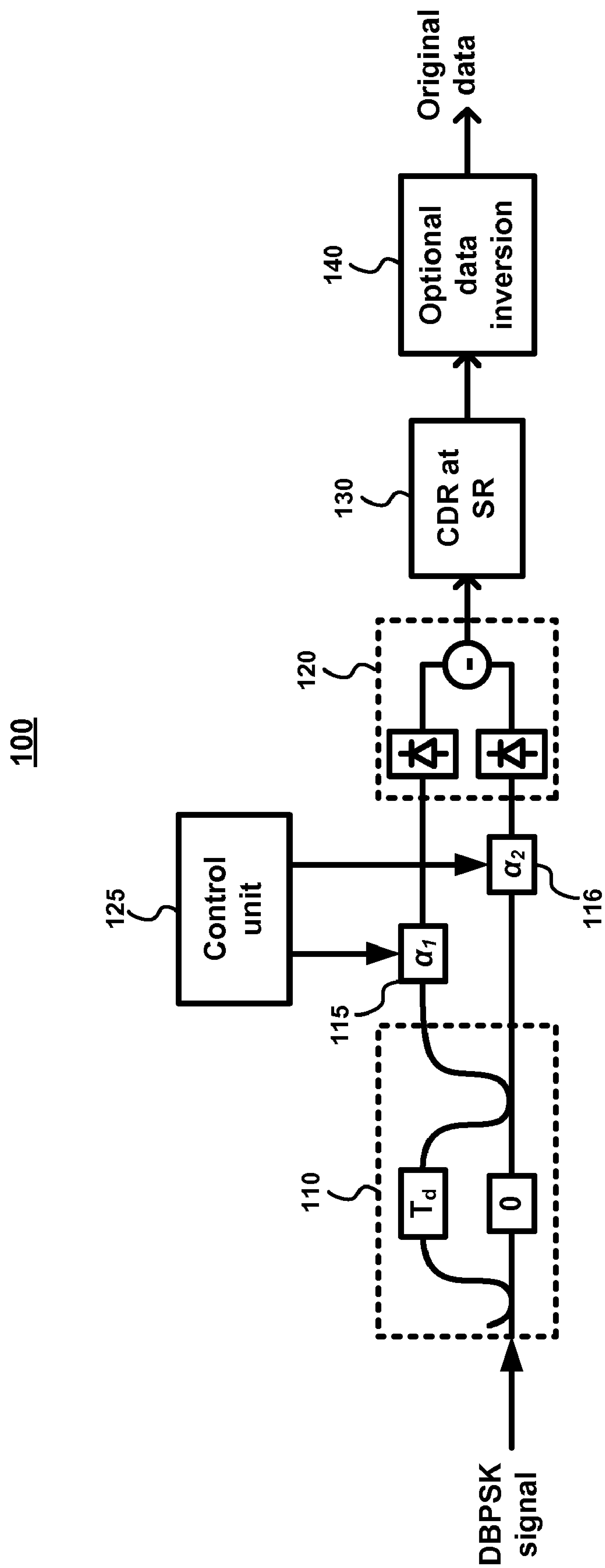

100
Original data
140
Optional data inversion
130
CDR at SR
120
-
125
Control unit
α1
α2
115
116
110
Td
0
DBPSK signal

FIG. 2

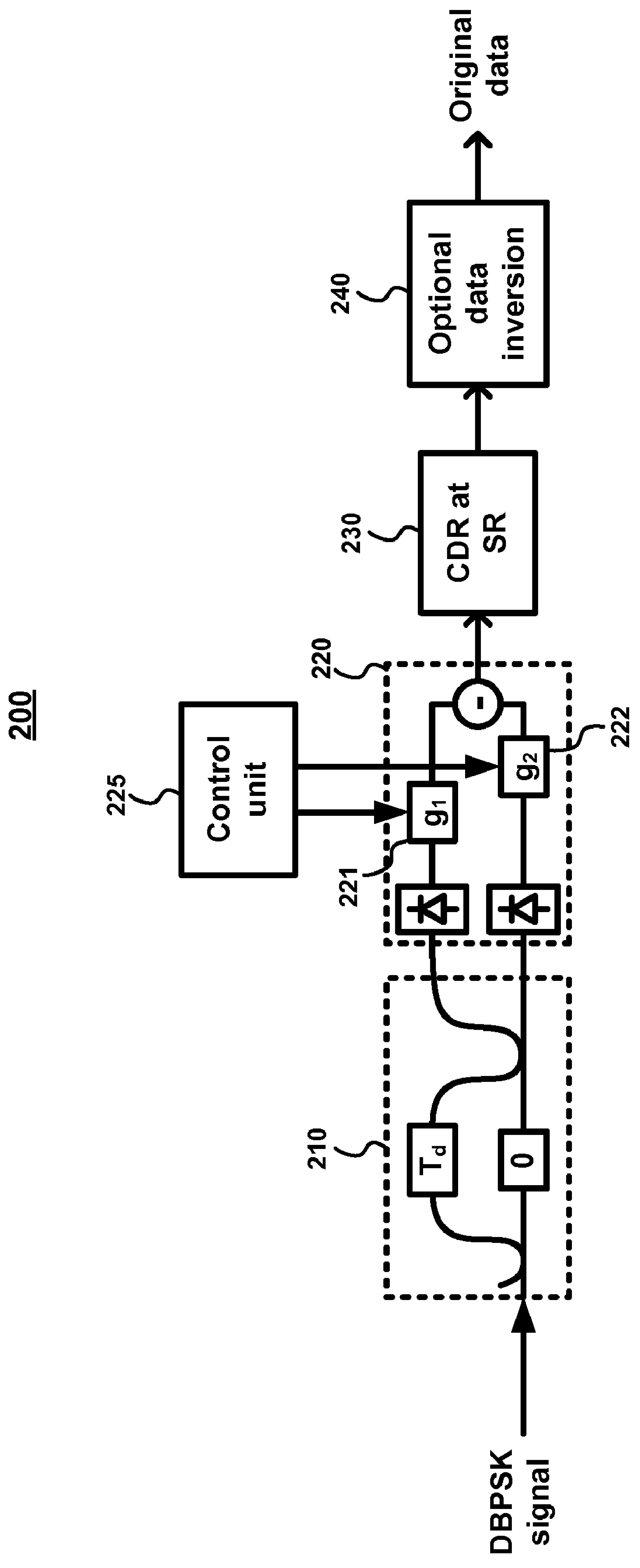

200
DBPSK signal
210
T_d
0
220
221
222
225
Control unit
g_1
g_2
-
230
CDR at SR
240
Optional data inversion
Original data

FIG. 3

300

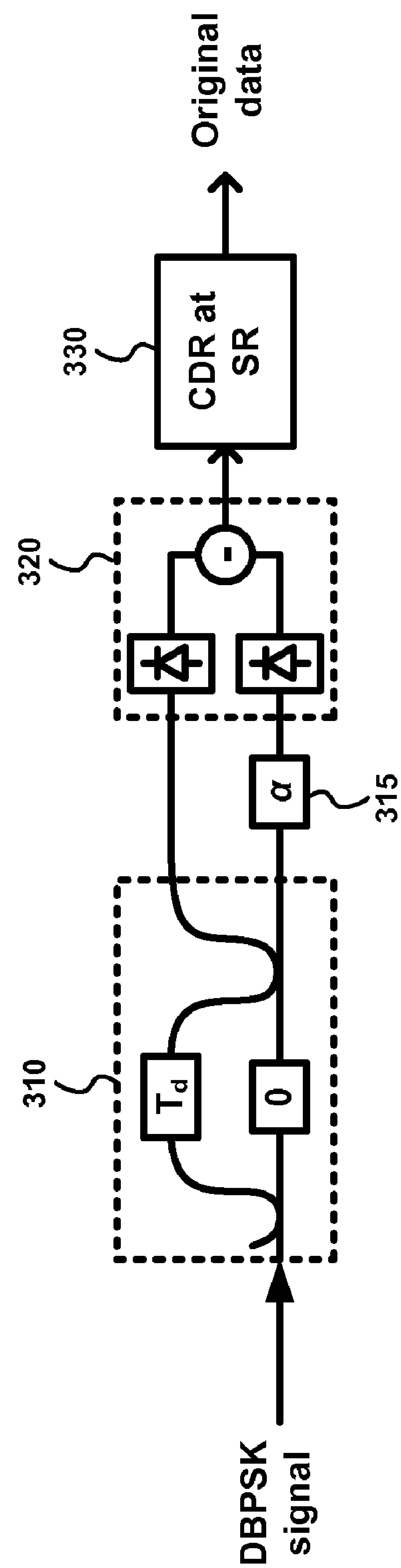


FIG. 4

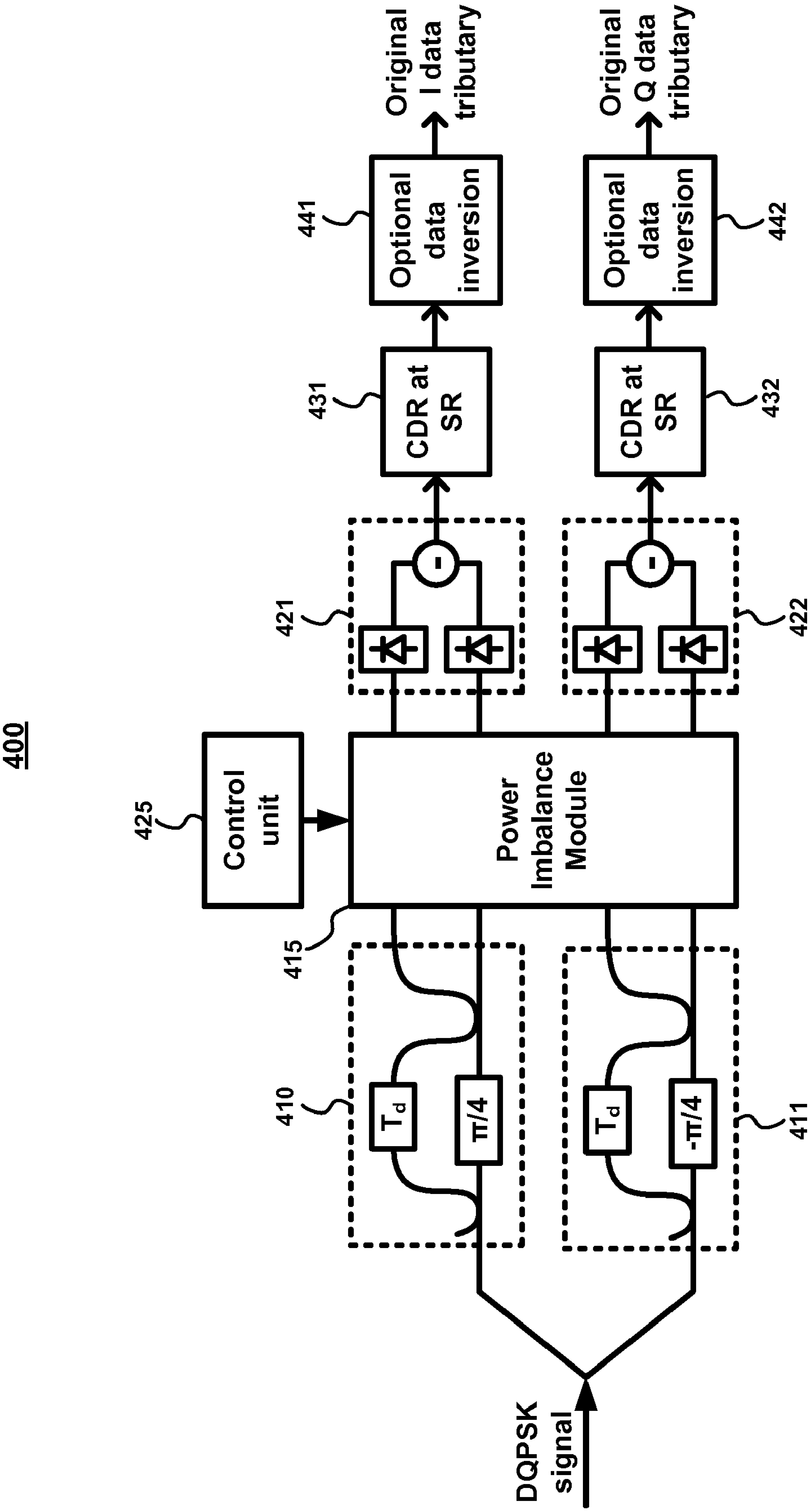

400
DQPSK signal
410
Td
π/4
411
Td
-π/4
415
Power Imbalance Module
425
Control unit
421
422
431
CDR at SR
432
CDR at SR
441
Optional data inversion
442
Optional data inversion
Original I data tributary
Original Q data tributary

FIG. 5

SYSTEM AND METHOD FOR RECEIVING HIGH SPECTRAL EFFICIENCY OPTICAL DPSK SIGNALS

FIELD OF THE INVENTION

The present invention relates to the field of optical communications, and more specifically to apparatus and methods related to the reception of differential phase shift keyed optical signals transmitted with high spectral efficiency.

BACKGROUND INFORMATION

Optical differential phase-shift keying (DPSK) is a promising modulation format that offers high receiver sensitivity, high tolerance to major nonlinear effects in high-speed transmissions, and high tolerance to coherent crosstalk. In optical DPSK transmission, data information is conveyed by the optical phase difference between adjacent bits. Optical DPSK modulation includes differential binary phase shift keying (DBPSK), differential quadrature phase shift keying (DQPSK), and other related format variants.

To increase the capacity of optical transport networks, 40-Gb/s channels are being considered to replace the 10-Gb/s channels currently carried on these networks. Most of the core transport networks_are based on dense wavelength-division multiplexing (DWDM) with a channel spacing of 50 GHz, as specified by the International Telecommunication Union (ITU). This spacing is illustrated schematically in FIG. **1**A, with Δf_{min}=50 GHz. Due to the much wider optical spectrum of a 40-Gb/s DBPSK signal, as compared to that of a typical 10-Gb/s signal, there is a severe penalty due to the tight optical filtering when transmitting the 40-Gb/s binary signals over the 50-GHz channel grid. This filtering penalty becomes even larger when multiple reconfigurable optical add/drop multiplexers (ROADMs) incorporating elements such as wavelength selective switches (WSS) are also inserted in the transmission system, as is common in most of today's transparent optical networks, such as that schematically depicted in FIG. **1**B. For example, in the network **10** illustrated, a signal may be routed via multiple ROADM/WSS **11**-**14** between its origin **21** and its destination **22**. This makes it difficult to transmit, with high spectral efficiency, such high-speed DPSK signals in a typical DWDM system.

An existing approach to achieve high spectral efficiency is to use bandwidth-efficient modulation formats such as DQPSK and duobinary. DQPSK, however, requires more complex and expensive transmitters and receivers, and duobinary has poorer receiver sensitivity than DBPSK and DQPSK.

SUMMARY OF THE INVENTION

In an exemplary embodiment, the present invention provides an optical differential phase-shift keying (DPSK) receiver which employs an optical delay interferometer (ODI) to demodulate a received optical DPSK signal. In accordance with the present invention, the ODI demodulator has a free spectral range (FSR) that is larger than the symbol rate (SR) of the DPSK signal to be demodulated. Moreover, the receiver includes means for introducing an additional power imbalance between the signals corresponding to the two outputs of the ODI demodulator, wherein the additional power imbalance is related to the ratio of FSR to SR. When judiciously chosen, the additional power imbalance increases the signal tolerance to tight optical filtering, thereby achieving high spectral efficiency in applications such as dense wavelength-division multiplexing (DWDM). The additional power imbalance can be implemented electrically, using electrical attenuation or amplification circuitry, or optically, using optical attenuation. The introduced power imbalance can be fixed or adjustable. In order to accommodate the potential ambiguity in the polarity of the received data, polarity detection and recovery circuitry may also be used.

Embodiments of the present invention can be applied, for example, to the transmission of 40-Gb/s differential binary phase shift keying (DBPSK) signals over a 50-GHz DWDM grid, as well as 100-Gb/s differential quadrature phase-shift keying (DQPSK) signals over a 50-GHz grid. Such embodiments enable 40-Gb/s DBPSK and 100-Gb/s DQPSK signals to be carried over DWDM systems having a 50-GHz minimum channel spacing with improved performance in terms of system reach and ROADM support.

Further embodiments of the present invention also provide other benefits such as adaptively optimizing the performance of the signal reception under different filtering conditions by adjusting the power ratio without changing the delay or FSR of the ODI, thereby making the signal reception hitless or free of interruption.

The aforementioned and other features and aspects of the present invention are described in greater detail below.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1**A illustrates the channel spacing in a dense wavelength-division multiplexing (DWDM) scheme; and FIG. **1**B is a schematic representation of a typical optical network with multiple reconfigurable optical add/drop multiplexers (ROADMs) and wavelength selective switches (WSS).

FIG. **2** is a block diagram of an exemplary embodiment of a differential binary phase shift keying (DBPSK) receiver comprising an optical power imbalance module.

FIG. **3** is a block diagram of an exemplary embodiment of a DBPSK receiver comprising an electrical power imbalance module.

FIG. **4** is a block diagram of a further exemplary embodiment of a DBPSK receiver.

FIG. **5** is a block diagram of an exemplary embodiment of a differential quadrature phase shift keying (DQPSK) receiver.

DETAILED DESCRIPTION

FIG. **2** is a block diagram of an exemplary embodiment of a differential binary phase shift keying (DBPSK) receiver **100** in accordance with the present invention. It is contemplated that the receiver **100** can be used, for example, to receive DBPSK signals, whose data rate is nominally 43 Gb/s and can range from about 40 Gb/s to 50 Gb/s, transmitted over a dense wavelength-division multiplexing DWDM system (FIG. **1**B) with 50-GHz minimum channel spacing Δf_{min}=50 GHz (FIG. **1**A).

The receiver **100** comprises an optical delay interferometer (ODI) **110** for demodulating a received optical DBPSK signal at its input. In general, an ODI has two optical paths with different lengths. The length difference between the two paths causes a time delay T_d between the optical signals traveling along the two paths, and the delay equals the reciprocal of the free spectral range (FSR) of the ODI, i.e., FSR=$1/T_d$. In accordance with the present invention, the ODI **110** has an FSR that is greater than the symbol rate (SR) of the DBPSK signal to be demodulated. In a exemplary embodiment in accordance with the present invention, the FSR is preferably in a range of:

$$1.15SR \leqq FSR \leqq 2.5SR, \quad (1)$$

where FSR is in units of GHz and SR is in units of Gbaud.

The constructive output port of the ODI **110** is coupled via an optical attenuator **115** to a first input of a balanced detector **120**, whereas the destructive output port of the ODI **110** is coupled via a second optical attenuator **116** to a second input of the balanced detector **120**. The optical attenuators **115** and **116**, with variable attenuation α_1 and α_2 respectively, are controlled by a control unit **125** to adjust the ratio of signal powers associated with the ODI constructive and destructive ports, P_{con} and P_{des}, respectively. The attenuators **115** and **116** introduce an incremental power imbalance, or change in the power ratio between the signals which is additional to the natural power ratio when the powers of the two signals are not thusly modified. For example, the additional adjustment of the power ratio P_{con}/P_{des} introduced by the attenuators **115** and **116** may be between −6 dB and 2 dB, depending on the degree of optical filtering to which the received DBPSK signal has been subjected, with more attenuation preferably introduced for less filtering. Here, an adjustment of 2 dB of the power ratio P_{con}/P_{des} means a relative increase of P_{con} over P_{des} by 2 dB, or by about 58%. As such, signal performance can be optimized under different filtering conditions adaptively (without changing the delay or FSR of the ODI) by adjusting the power ratio.

Although the exemplary embodiment of FIG. **2** shows an optical attenuator coupled to each of the constructive and destructive ports of the ODI **110**, it is possible in accordance with the present invention to have alternative embodiments with an attenuator coupled to only one of the ODI ports. For instance, if the additional adjustment of the power ratio P_{con}/P_{des} is to be less than zero (i.e., only the signal of the constructive port need be attenuated), the attenuator **116** can be eliminated.

Moreover, for applications in which it is not necessary to vary the attenuation (e.g., the filtering conditions are substantially constant), attenuation can be realized, for example, with a fixed attenuator or by imperfect optical coupling in at least one of the output ports of the ODI **110**. Using well known techniques, the optical coupling can be set upon fabrication to provide the desired degree of attenuation.

The output of the balanced detector **120** is provided to a clock and data recovery (CDR) circuit **130**, which recovers the data encoded in the received signal and a clock at the symbol rate (SR). In order to accommodate the potential ambiguity in the polarity of the received data, a data inversion circuit **140** may also be included to invert the data recovered by the CDR circuit **130**. The CDR and data inversion circuits can be implemented in known ways.

As a further alternative in accordance with the present invention, the power ratio adjustment can be achieved with electrical means. FIG. **3** shows a further exemplary embodiment of a receiver **200** in which the power ratio adjustment is carried out using electronic amplifier and/or attenuator circuitry. The receiver **200** comprises electronic amplifiers (and/or attenuators) **221** and **222** which amplify and/or attenuate the constructive and destructive outputs, respectively, of the ODI **210** after they have been detected and converted to electrical signals. The amplification and/or attenuation (g_1, g_2) provided by the amplifiers (and/or attenuators) **221** and **222** can be varied under the control of a control unit **225**. A clock and data recovery (CDR) circuit **230** and an optional data inversion circuit **240**, as described above, recover the original data.

Although the exemplary embodiment of FIG. **3** shows an electronic amplifier (and/or attenuator) for each of the constructive and destructive ports of the ODI **210**, it is possible in accordance with the present invention to have alternative embodiments with an amplifier (attenuator) for only one of the ODI ports.

In an exemplary embodiment, the power adjustment can be set in accordance with the following relation:

$$\Delta(P_{con}/P_{des}) \approx (SR/FSR - 0.75) \times 15 \text{ dB}. \quad (2)$$

For example, for a symbol rate (SR) of 43 Gb/s, the additional power ratio adjustments on (P_{con}/P_{des}) would be approximately 1.7 dB, −1.6 dB, and −4.8 dB for FSRs of 50 GHz, 67 GHz, and 100 GHz, respectively. If the FSR and SR obey the relationship (1), the additional power ratio adjustment $\Delta(P_{con}/P_{des})$ would have a range of approximately −5.25 dB to 1.8 dB.

FIG. **4** is a block diagram of a further exemplary embodiment of a receiver **300** in accordance with the present invention. The receiver **300** comprises an ODI **310** demodulator with an FSR that is equal to the WDM channel spacing, Δf_{min}. Thus, in the case of 50 GHz channel spacing, the FSR of the ODI **310** would be 50 GHz, and T_d would be 20 ps. As such, the FSR of the ODI **310** would be about 16% larger than the symbol rate of a 43 Gb/s DBPSK signal. According to the relationship (2), the desired power adjustment would be 1.65 dB, or P_{des} would be decreased relative to P_{con} by 1.65 dB, or by about 32%.

In the exemplary embodiment of FIG. **4**, the additional power imbalance is introduced by a fixed optical attenuation **315** between the destructive output port of the ODI **310** and the balanced detector **320**. The attenuation **315** can be implemented, for example, by imperfectly coupling the destructive port of the ODI **310** to the detector **320** to provide a fixed optical attenuation **315** to the corresponding signal. Alternatively, the attenuation **315** can be implemented with a discrete power imbalance module or block, as described above.

A CDR circuit **330**, as described above, is shown for recovering the original data. A feature of the embodiment of FIG. **4** is that the optional data inversion circuit may no longer be needed since the ODI **310**, whose FSR equals the WDM channel spacing Δf_{min}, may be configured to demodulate any one of the WDM channels with a fixed nominal condition. This feature can also be exploited to realize colorless operation where no change in ODI settings is needed when the wavelength of the received WDM signal changes.

FIG. **5** is a block diagram of yet a further exemplary embodiment of a receiver **400** in accordance with the present invention. The receiver **400** can demodulate differential quadrature phase-shift keying (DQPSK) signals, such as may be transmitted over a DWDM system with 50-GHz minimum channel spacing. For a DQPSK signal with a net data rate of 100 Gb/s, for example, the raw data rate is nominally 113 Gb/s and can range from about 107 Gb/s to about 125 Gb/s when the overhead for processes such as forward error correction (FEC) is included.

The receiver **400** comprises a DQPSK demodulator including a pair of ODIs **410** and **411** for demodulation of the in-phase and quadrature-phase components of the DQPSK signal. In an exemplary embodiment, the FSR of the DQPSK demodulator is 100 GHz. As such, the FSR of the ODIs **410** and **411** is about 77% larger than the symbol rate of a 113 Gb/s DQPSK signal. According to the relationship (2), the desired power adjustment would be −2.8 dB, or in other words, P_{con} (of each ODI) would be decreased relative to P_{des} (of each ODI) by 2.8 dB, or by about 48%.

The outputs of the ODIs **410** and **411** are provided to a power imbalance module **415**. The in-phase and quadrature-phase outputs of the power imbalance module **415** are coupled to balanced detectors **421** and **422**, respectively. The power imbalance module **415** can be implemented as described above by subjecting the signals at the constructive and/or destructive ports of the ODIs **410** and **411** to optical attenuation, such as by an optical attenuator or by providing imperfect optical coupling. Alternatively, as described above, an electrical implementation of a power imbalance module arranged after the conversion of the optical signals to electrical form can be used. Moreover, the power imbalance module **415** may provide a fixed power imbalance or a variable power imbalance under the control of a control unit **425**.

CDR circuits **431** and **432** and optional data inversion circuits **441** and **442**, as described above, follow the detectors **421** and **422**, respectively, for recovering the original in-phase and quadrature-phase data tributaries.

As disclosed herein, the present invention offers good signal performance when receiving high spectral efficiency DPSK signals transmitted over conventional DWDM systems. Moreover, further embodiments of the present invention also provide other benefits such as a mechanism for optimizing the signal performance under different filtering conditions adaptively (without changing the delay of the ODI) by adjusting the power ratio, and allowing hitless receiver operation. Such embodiments of the present invention thereby provides overall system performance improvement and easy implementation when transmitting DPSK signals in high spectral efficiency systems.

It is understood that the above-described embodiments are illustrative of only a few of the possible specific embodiments which can represent applications of the invention. Numerous and varied other arrangements can be made by those skilled in the art without departing from the spirit and scope of the invention.

What is claimed is:

1. An optical receiver for receiving a differential phase-shift keyed (DPSK) optical signal from a wavelength-division multiplexed (WDM) optical transmission system, the optical receiver comprising:

a demodulator, the demodulator including an optical delay interferometer (ODI) having:

an optical input for receiving the DPSK optical signal,

a constructive optical output associated with a constructive signal based on the DPSK optical signal, and

a destructive optical output associated with a destructive signal based on the DPSK optical signal; and

a power imbalance module that provides an additional relative power difference between the constructive and destructive signals,

wherein the ODI has a free spectral range (FSR) that is larger than a symbol rate (SR) of the DPSK optical signal, and the additional relative power difference is dependent on the ratio between SR and FSR according to the following relation:

$$\Delta(P_{con}/P_{des}) \approx (SR/FSR-0.75)\times 15 \text{ dB},$$

where P_{con} is the power of the constructive signal, P_{des} is the power of the destructive signal, and $\Delta(P_{con}/P_{des})$ is the additional power difference in dB.

2. The optical receiver of claim **1**, wherein 1.15 SR≦FSR≦2.5 SR.

3. The optical receiver of claim **1**, wherein the power imbalance module includes an optical attenuator.

4. The optical receiver of claim **3**, wherein the optical attenuator is realized by imperfect optical coupling in at least one of the optical outputs of the ODI.

5. The optical receiver of claim **1** wherein the power imbalance module includes at least one of an electronic attenuator and an electronic amplifier.

6. The optical receiver of claim **1**, wherein the DPSK optical signal is a differential binary phase-shift keying (DBPSK) signal.

7. The optical receiver of claim **1**, wherein the DPSK optical signal is a differential quadrature phase-shift keying (DQPSK) signal.

8. The optical receiver of claim **1**, wherein the FSR of the ODI is equal to a channel spacing of the WDM optical transmission system.

9. A method for receiving a differential phase-shift keyed (DPSK) optical signal from a wavelength-division multiplexed (WDM) optical transmission system, the method comprising:

demodulating the DPSK optical signal with an optical delay interferometer (ODI) having:

an optical input for receiving the DPSK optical signal,

a constructive optical output associated with a constructive signal derived from the DPSK optical signal, and

a destructive optical output associated with a destructive signal derived from the DPSK optical signal; and

providing an additional relative power difference between the constructive and destructive signals,

wherein the ODI has a free spectral range (FSR) that is larger than a symbol rate (SR) of the DPSK optical signal, and the additional relative power difference is dependent on the ratio between SR and FSR according to the following relation:

$$\Delta(P_{con}/P_{des}) \approx (SR/FSR-0.75)\times 15 \text{ dB},$$

where P_{con} is the power of the constructive signal, P_{des} the power of the destructive signal, and $\Delta(P_{con}/P_{des})$ is the additional power difference in dB.

10. The method of claim **9**, wherein 1.15 SR≦FSR≦2.5 SR.

11. The method of claim **9**, wherein providing an additional relative power difference comprises optically attenuating at least one of the constructive and destructive signals.

12. The method of claim **11**, wherein the at least one of the constructive and destructive signals is optically attenuated by imperfectly optically coupling at least one of the optical outputs of the ODI.

13. The method of claim **9**, wherein providing an additional relative power difference comprises at least one of electronically attenuating and electronically amplifying at least one of the constructive and destructive signals.

14. The method of claim **9**, wherein the DPSK optical signal is a differential binary phase-shift keying (DBPSK) signal.

15. The method of claim **9**, wherein the DPSK optical signal is a differential quadrature phase-shift keying (DQPSK) signal.

16. The method of claim **9**, wherein the FSR of the ODI is equal to a channel spacing of the WDM optical transmission system.

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